EVALUATION AND OPTIMIZATION RESEARCH OF GROUND SOURCE HEAT PUMP

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Abstract

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Abstract

Nowadays energy efficiency and environmental protection have got particular attention. After the sustainable development theory had been put forward decades ago. Ground source heat pump with air conditioning system has pointed out a new way for saving energy as well as reducing air pollution and carbon emission.

This thesis describes the theories of ground source heat pump and lists the differences between ground source heat pump with air conditioning system and other air conditioning systems. After that, a detailed description of category of heat pump categories is given. Then, main indicators are listed out for comparing the technology and economy of the ground source heat pump system.

As the heat exchanger is an important part of the ground source heat pump, in the last part of the thesis, designing methods of heat exchanger are studied and analyzed, including load calculation, pipe layout, choice of tubes and its material, antifreeze method, and calculation of pressure drop.

Keywords
Heat pump, Ground source heat pump with air conditioning system, Heat exchanger

CONTENTS

1 INTRODUCTION

1.1 Energy situation and background

Over the coming decade, the world faces a serious challenge in meeting a growing global energy need, while mitigating the pollution to the environment. China is a country not only with the rapidest rate of development, but also with the biggest energy consumption in the world. In 2006, China's GDP accounted for about 5.5% of the world, however, the coal consumption accounted for 15% of the world total consumption.

As one of the biggest energy consumption project, building energy consumption counts for 28% of the total national energy consumption in China. The figure is even higher in developed countries, at 30%-40% (Li Shiguo, 2007, p.13). In particular, heating and refrigeration of residential buildings consume the most energy. There is a general consensus that the high pollution always goes hand in hand with high energy consumption. The house heating and refrigeration emit a large number of toxic gas and greenhouse gas, such as SO_2, NO_x and CO_2. After the energy crises in 1970s, Sustainable Development Theory has been proposed and developed. It has greatly promoted the development and research of new technology which can minimize the negative impact on the environment and increase energy efficiency. As a new heating and refrigeration technology, a ground source heat pump has pointed out a new way for saving energy as well as reducing air pollution and carbon emission.

1.2 Objective of the thesis

By analyzing the technology and economy of the ground source heat pump system and optimization designing of its ground heat exchanger, the thesis tries to explain the following issues: What is the ground source heat pump? How does it work? What are the differences between the ground source heat pump air-conditioning system and other air-conditioning systems? What are the technical and economical benefits of it? How to put it into practice? The final objective is to extend the ground source heat pump technology to the society.

1.3 Description of the thesis contents

The Chapter 1 gives a sketch of the structure and the principle of ground source heat pump system. Then this paper gives a detail description on categories of heat exchanger. After that, the history of the ground source heat pump system is briefly introduced.

In Chapter 2, the ground source heat pump with air conditioning system is compared with the air source heat pump system, the water source heat pump system and traditional central air-conditioning in terms of technology and economy. The main indices are given to evaluate the technology and economy of the ground source heat pump air-conditioning system.

The heat exchanger is an important part of the ground source heat pump air-conditioning and it is also the main difference from other traditional air-conditioning system. Chapter 3 gives detailed designing methods of heat exchanger, including load calculation, pipe layout, choice of tubes and its material, antifreeze method, calculation of pressure drop, etc. At the end of the chapter, the ground source heat pump air-conditioning system in the auditorium of Anhui Architecture & Engineering is taken as an example to show how to analyze and optimum design the ground loop heat exchanger.

2 BRIEF INTRODUCTION OF HEAT PUMP

2.1 The principle of heat pump

As a natural phenomenon, heat flows from height to low as water. It is also expressed by the second law of thermodynamics. However, people created a machine that is able to pump heat from low-temperature to high temperature, just like a pump could upgrade water from the low to the height. So the heat pump is a heat upgrade device. It consumes little energy, mining the heat tapped in environment and upgrades the heat grade.

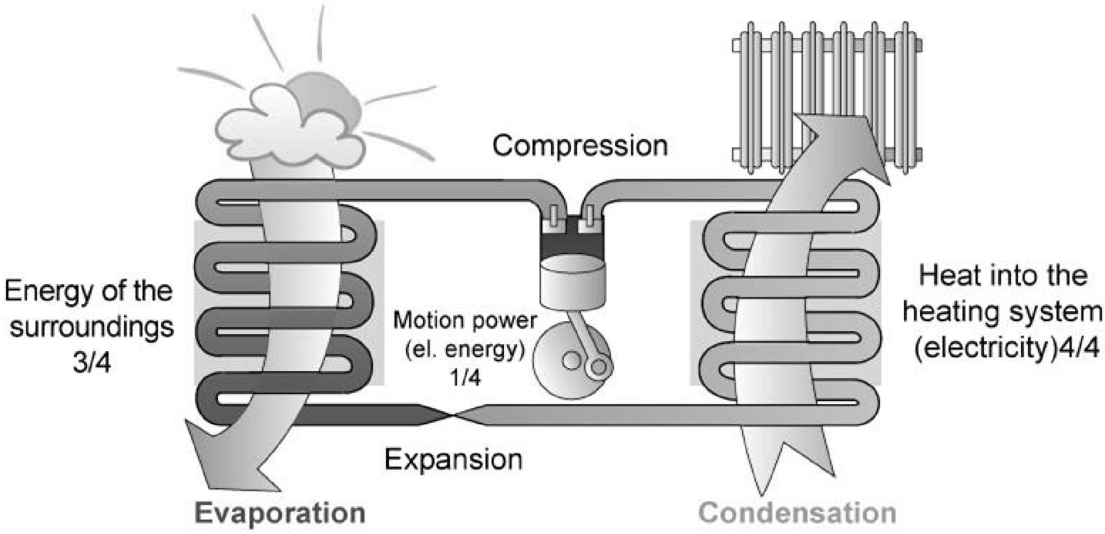


FIGURE 1. Heat pump operation (DAL Air Conditioning 2009)

FIGURE 1 shows the principle and the structure components of the heat pump; it consists of four parts:

The compressor is the heart of the heat pump. It compresses and transports the cyclic fluids from the low temperature pressure place to high temperature pressure place.

The evaporator is the equipment for heat absorption. It evaporates the liquid refrigerant coming from the reversing valve, and absorbs the heat from the surroundings.

The condenser is the equipment for heat release. It rejects the heat absorbed in the evaporator, suction and the compressor. Condense the refrigerant back to a liquid.

The reversing valve throttles and reduces pressure for the cyclic fluids to evaporator.

According to the second law of thermodynamics, the electricity power for the compressor provides compensation to the system. It makes the cyclic fluid absorb the heat from the low temperature environment and release them to a high temperature environment constantly.

2.2 The classification of heat pump

2.2.1 The introduction

During the heating process, a heat pump uses the heat from the condenser, and the evaporator extracts the heat from the outdoors. The medium where heat is extracted is called a heat source. By contrast, when refrigeration is in process, heat pump absorbs the heat from indoor, and condenser releases them to the environment which is referred to as cold source.

The heat pump using air as heat and cold source is called an air source heat pump. The air source heat pump has a long history in China. It becomes wide spread because of the convenience of installation and usage. However, the air temperature is quite different from region to region. The air source heat pump is typically used in the areas to the south of the Yangtze River. In the north part of China, the air average temperature in winter is lower than zero degrees centigrade. The low temperature not only results in poor stability but also causes problem of frosting and defrosting on heat exchangers.

The heat pump using water as heat and cold source is called a water source heat pump. Water is a good heat source for its high heat capacity and thermal conductivity. Generally the heating efficiency and capacity of the water source heat pump is better than the air source heat pump. But due to the limitation of water resources, the water source heat pump is bound to be less used.

A ground source heat pump is a central heating and/or refrigeration system that pumps heat to or from the ground. It uses the earth as a heat source (in the winter) or a heat sink (in the summer). This design takes advantage of the moderate temperatures in the ground to boost efficiency and reduce the operational costs of heating and refrigeration systems.

2.2.2 The classification of ground source heat pump

The ground source can be further classified into two subtypes: the solid and groundwater. Just as a slight clarification, unlike water source system, the temperature of groundwater is wholly independent of the atmospheric environment but surrounded and influenced by the underground environment.

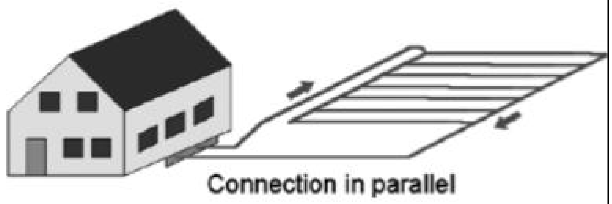
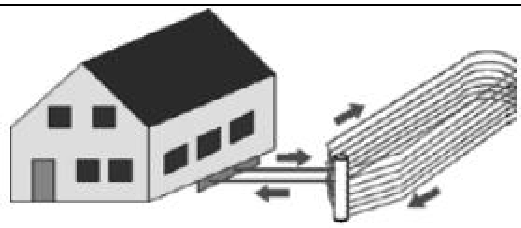
2.2.2.1 Ground- coupled heat pump

In the ground-coupled heat pump system, the ground-couple heater exchanger is fixed into the trench horizontally or assembled into a vertical shaft. The heat transfer fluid is circulated in a closed loop. The fluid never leaves the system, but rather travels back and forth in a loop between the heat pump and the earth connection.

2.2.2.1.1 Horizontal ground-coupled heat pump

The horizontal ground heat exchanger is the easiest and cheapest closed system to be installed. In order to get a larger area for heat transfer, different places use different patterns of ground-couple heat exchanger. The TABLE 1 shows four common horizontal heat exchangers.

TABLE 1. Four types of horizontal ground-coupled heat pump (RHVACT, 2011)

Type	Characteristics	Graphical representation
Horizontal ground heat exchanger	Simple structure Easy installation For wide open space	
		
Compact ground heat exchanger	Tight structure Saves the area	 Trench Collector
		 Slinky Collector

2.2.2.1.2 Vertical borehole ground-coupled heat pump

The borehole ground-coupled heat pump is well suitable to larger building where minimal damage of the landscaping is desired, or where little land is available for the heat pump. FIGURE 2 is a typical vertical borehole ground-coupled heat pump. The borehole is normally 45 to 150 m deep, it contains either one or two loops of pipe with a U-bend at the bottom. After the pipe has been inserted, the borehole is backfilled and grouted.

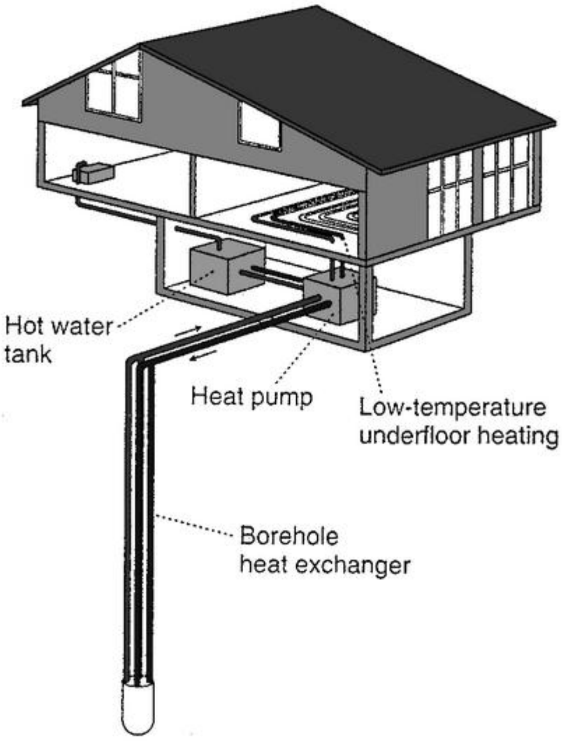


FIGURE 2. The application borehole ground-coupled heat pump (Air & Water Center, 2011)

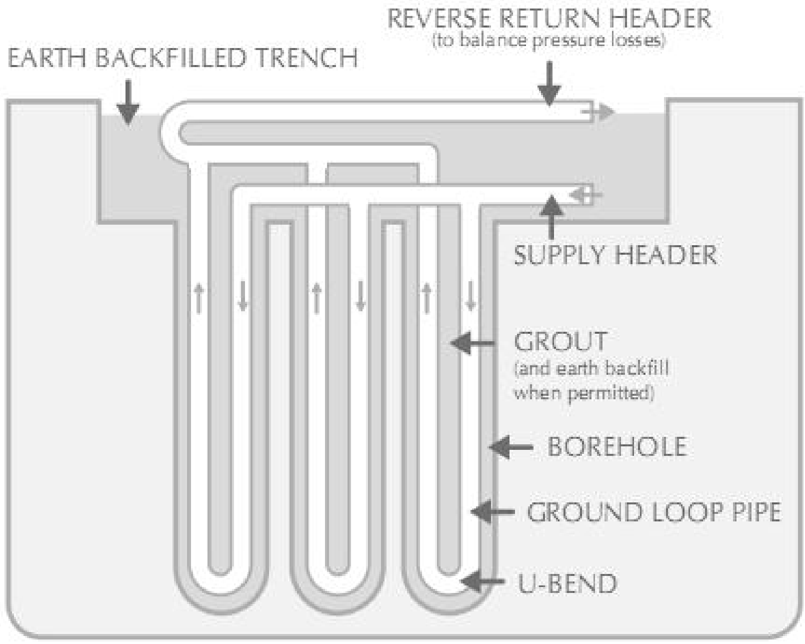


FIGURE 3. The borehole and U-bend heat exchanger (Minister of Natural Resources Canada, 2001 – 2005, 14.)

FIGURE 3 shows the structure of the borehole and the U-bend heat exchanger. In a standard borehole heat exchanger, plastic pipes (polyethylene or polypropylene) are installed in boreholes, and the remaining room is filled with a backfill material.

2.2.2.1.3 Groundwater heat pump

Contrary to the ground-coupled heat pump, a groundwater heat pump is an open loop system. This type of system uses ground water as the heat exchange fluid that circulates directly through the groundwater heat pump system. After the water circulated through the system, it returns to the ground through the well, or surface discharge. This option is obviously practical only where there is an adequate supply of relatively clean water, and all local codes and regulations regarding groundwater discharge are met.

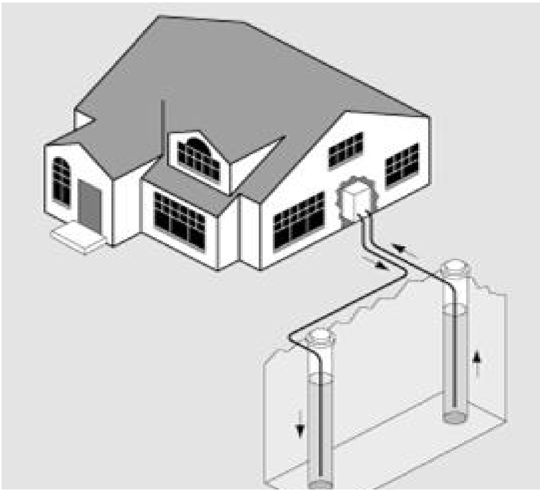


FIGURE 4. Ground water heat pump (Norbert Lechner, 2008, 522)

As FIGURE 4 shows, a complete groundwater heat pump consists of one open water loop and one closed building loop. These two separate loops isolate the heat pump from the groundwater, protecting its heat exchanger from the potential fouling and corrosion.

2.3 The development of ground source heat pump

2.3.1 The development of ground source heat pump in western countries

The ground source heat pump is one of the fastest growing applications of renewable energy in the world. In the past 10 years, the annual growth rate of the ground source heat pump is around 10% in about 30 countries. Most of this growth has occurred in the United States and Europe.

In 1950s, the British experts Sumner and Von Cube installed the first ground source heat pump for residential heating. In 1974, Europe started 30 research projects to develop the ground source heat pump technology and accumulated the experience. However, all the ground source heat pumps are just used for heating, and most of them are using Horizontal Heat Exchanger. From 1971 to 1978, the United State tried variety of types of heat exchanger, and the solar thermal collector was introduced and merged with the heat pump system. In this period, the metal tubes were replaced by plastic tubes.

Nowadays the worldwide installed capacity is estimated at almost 12,000 MWt and the annual energy use is about 20,000 GWh. The actual number of installed units is around 1,100,000. TABLE 2 lists the countries with the highest use of GHPs.

TABLE 2. Leading Countries Using GHP

Country	MWt	GWh/yr	Number Installed
Austria	275	370	23,000
Canada	435	600	36,000
Germany	640	930	46,400
Sweden	2,300	9,200	230,000
Switzerland	525	780	30,000
USA	6,300	6,300	600,000

2.3.2 The development ground source heat pump in China

Heat pump technology research started in 1950s in China. In 1960s heat pump was preliminarily applied in industry. In 1965, the first window-type heat pump with air conditioning CKT-3A was made by Shanghai Refrigerators Plant. In the same year, the first water-cooled heat pump air conditioner was made. The development of the heat pump air conditioner was quite slow. Till the end of 1990s, following the changes of the national energy policy and the emphasis of the environment protection, the heat pump technology has developed very fast, especially in Beijing. According to incomplete statistics, by the end of 2006, there were over 8 million m^2 buildings using the ground source heat pump for heating and refrigeration.

3 TECHNICAL AND ECONOMIC ASSESSMENT FOR GROUND SOURCE HEAT PUMP

3.1 Technical evaluation

3.1.1 System configuration

As showed in FIGURE 5, the ground source heat pump system can be divided into three parts: 1) an outdoor heat exchanger, 2) a ground source heat pump unit, 3) an air conditioner terminal device. The heat is transferred between the three parts by the heat transfer medium. There is one loop in each part: heat exchanger loop, refrigerant loop and air loop.

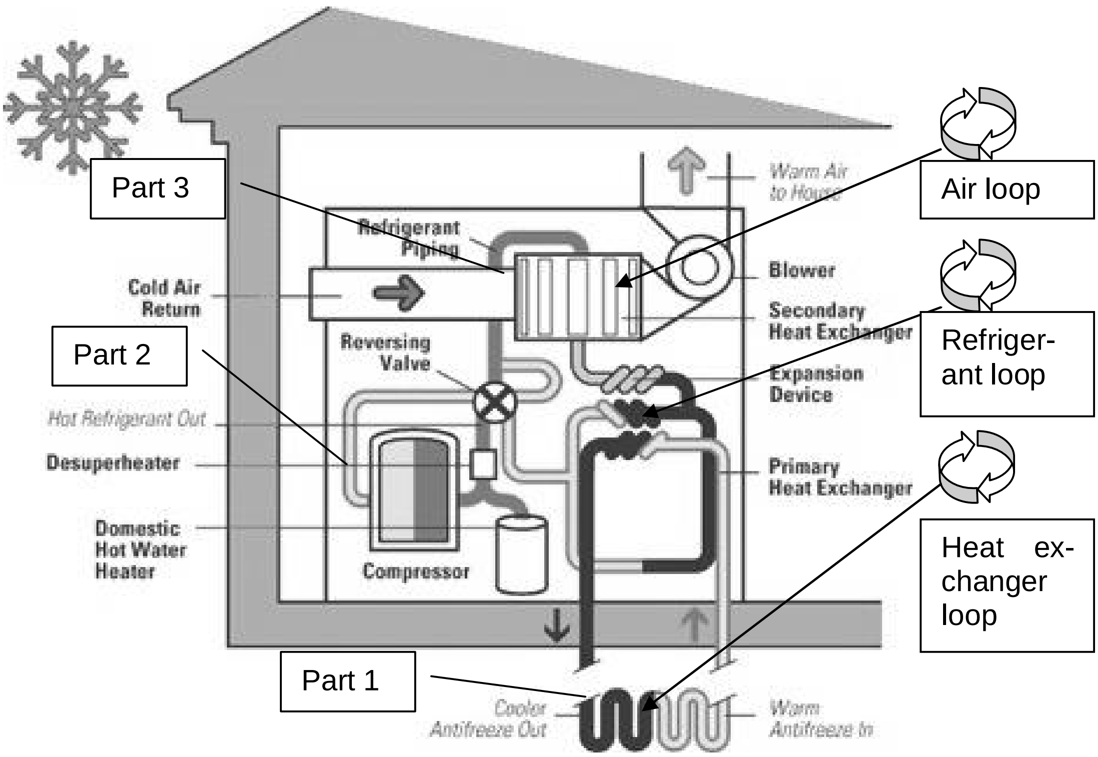


FIGURE 5. Ground source heat pump (Treehugger, 2008)

3.1.2 Operation of ground source heat pump

3.1.2.1 Heating process

In heating process, the heat transfers to the air in the building from the ground and system operation. In the case of system operation, the primary heat exchanger is the evaporator, and the secondary heat exchanger is the condenser.

In heat exchanger loop, the water from the primary heat exchanger is absorbed the heat from the earth through the circulating water pipe. This heat is brought back to the primary heat exchanger. There the refrigerant evaporates and absorbs the heat from the water.

In refrigerant loop, the evaporated refrigerant is compressed into the high temperature and high pressure steam, with the heat from the ground and the electricity wasted on the compressor. After the heat is absorbed by the indoor air, the refrigerant is condensed into liquid. The liquid refrigerant then flows to the expansion device which releases the pressure and brings down the temperature. In the end, the liquid refrigerant with low pressure and temperature goes back to the primary heat exchanger. There the liquid is evaporated by absorption of the temperature of the heat exchange loop. The whole loop is described in FIGURE 6.

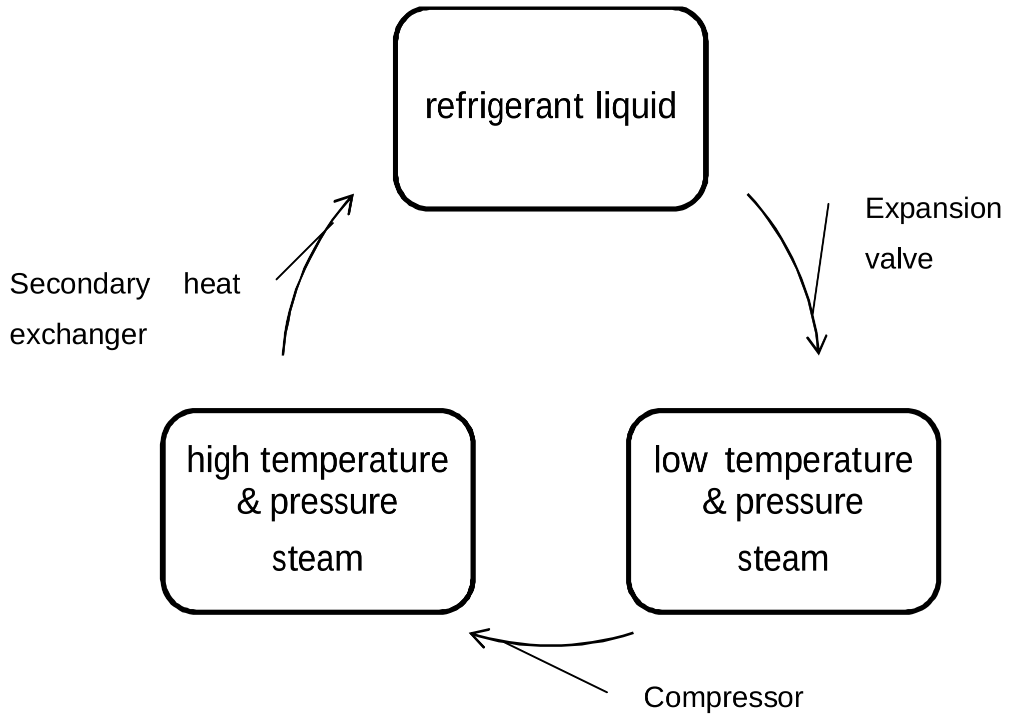


FIGURE 6. Refrigerant loop

In air loop, the outdoor air and return air enter in secondary heat exchanger. After absorbing the heat of the high temperature and pressure refrigerant, it is distributed to every area of the building through the air distribution system.

3.1.2.2 Refrigeration process

In refrigeration process, the system takes the heat from the indoor environment and the compressor to the earth and releases them, so the condenser is the primary heat exchanger, and the secondary heat exchanger is the evaporator.

In air loop, the outdoor air and return air enter in secondary heat exchanger. There they are cooled down by the low temperature and pressure refrigerant. After that, it is distributed to every area of the building through the air distribution system.

In refrigerant loop, the evaporated refrigerant is compressed into the high temperature and high pressure steam, with the heat from the air loop and the electricity wasted on the compressor. After the heat is absorbed by the water in heat exchanger loop, the refrigerant is condensed into liquid. The liquid refrigerant then flows to the expansion device which releases the pressure and brings down the temperature. In the end, the liquid refrigerant with low pressure and temperature goes back to the secondary heat exchanger. There the liquid is evaporated by absorption the temperature of the air loop.

In heat exchanger loop, the warmed water from the primary heat exchanger is cooled down by the ground, and it releases the heat to the ground.

The heating process and refrigeration process can be shifted by switch to the reversing valves to change the direction of the refrigerant flow.

3.1.3 The specialty of the ground source heat pump

As an air condition technique with high efficiency, environment friendliness and energy saving, ground source heat pump technology has the following specialties:

1. Ground source heat pump technology is one kind of utilization of renewable energy technology. The heat and cold source of the system is the shallow

ground of the earth (less than 400 m deep), which absorbs 46% of the solar energy that is 500 times the total energy used by human beings each year (See FIGURE 7).

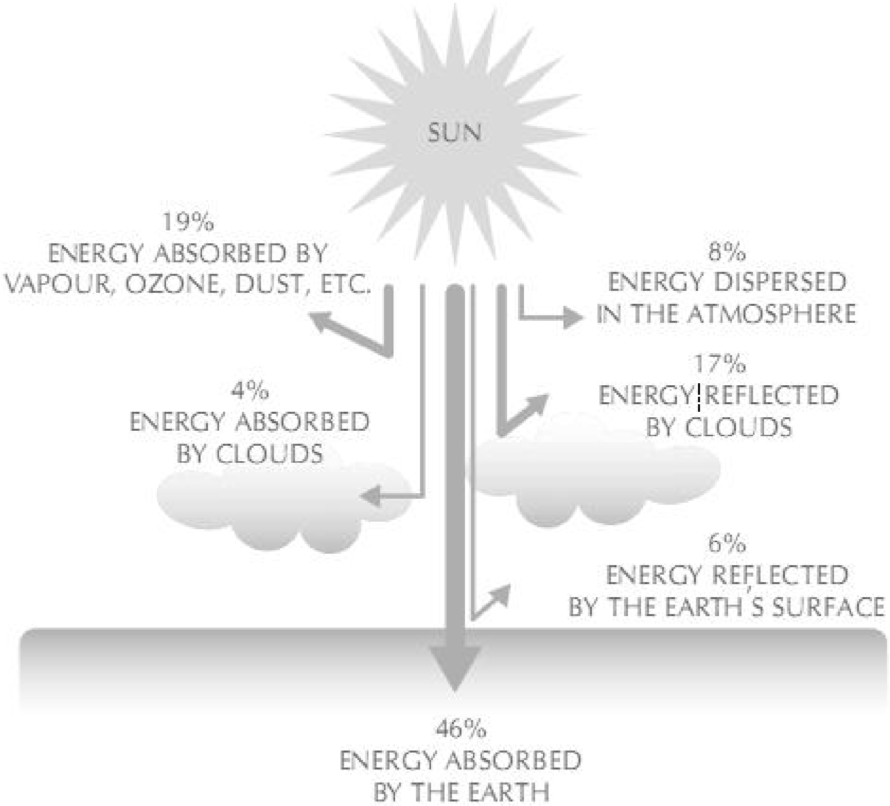


FIGURE 7. The energy from the sun to the earth. (Minister of Natural Resources Canada, 2001 – 2005, 5.)

2. Ground source heat pump technology is high efficient and energy-saving air condition technology. The temperature of the shallow ground is relatively stable all year round; it is warmer than the indoor temperature in winter and colder than the indoor temperature in summer. In heating process, 70% of energy comes from the ground, and 30% of energy is from the electricity that moves the temperature form the ground to the indoor environment. Conversion efficiency ratio of the ground source heat pump could be 4.7. Compared to electric boiler, it can save two-thirds of electricity energy. Comparing to the fuel boiler, the ground source heat pump can save even more than half energy. The heat coefficient of the ground could be 3.5-4.7. It's 40% higher than the traditional air conditioner. The high energy efficiency of the ground source determines the low operation costs. In addition, the ground source heat pump also has the feature of the little maintenance, low repair costs and long service life.

3. Ground source heat pump technology is environmental-friendly. Without a boiler, so the ground source heat pump will reduce the emissions of the warm house gas. The heat exchanger loop is closed, so no pollution can leak into the shallow ground. For the above reasons, the ground source heat pump system can be installed in the living area without burning, smoke and solid wastes.

   TABLE 3. CO2 emissions per kWh for different fuels (Kensa Engineering, 2009, 2.)

Fuel	Kg CO_2/kWh
Electricity	0.54
Natural gas	0.19
Coal	0.3
Oil	0.25
Ground source heat pump	0.135

   TABLE 3 lists the CO_2 emissions per kWh for different fuels. Although the ground source heat pump uses electricity, its CO2 reduction is 29% and 46% on oil.

4. With multi-functions, the system has wide application possibilities. The ground source heat pump will not only be used for heating and refrigeration, but it also provides domestic hot water. It can be used in hotels, emporiums, office buildings, schools, and so on.

5. Being safe and reliable. There are no explosion and combustion hazards for the ground source heat pump. The heat exchanger using high density poly-ethylene plastic pipe with a long lifetime of up to 50 years and the heat pump unit has 15 years' service life. It can significantly reduce the manpower and maintenance costs.

3.2 Economic evaluation

3.2.1 The need for economic evaluation

The economy factors such as investment, and operation fees will directly influence the selection of the ground source heat pump for customers. For the short history of the application, the summary work about operating economy in China needs to be improved. So the economic analysis is necessary for the application and development of the ground source heat pump.

3.2.2 Evaluation criteria

In order to get a comprehensive evaluation, the economy can be divided into heating economy and refrigeration economy. When considering the heating economy, the ground source heat pump should be compared with coal boiler, oil boiler and natural gas boiler. About the refrigeration economy, the ground source heat pump must be compared with the air cooling conditioner and central air-conditioner. The following parameters could be the evaluative criteria:

1. Initial investment

   The initial investment is the sum of investment on each part of the system. It consists of the land costs, original equipment costs, equipment installation costs and others.

2. Annual operating costs

   The annual operating costs is the sum of the costs on operation of each part. It includes the fuel, water, electricity, management fee, executive salary, maintenance and depreciation.

   The main energy costs on the heat pump operation are the heat energy and electrical energy. Heat energy is used for transferring between the ground and indoor environment. Electrical energy is the real cost, and it is mainly used on three parts of the system: the heat pump compressor, the throttle valve and the air circulating system, the most of energy costs fall on the compressor. Taking Trane wpvd200 heat pump as an example, we can get the following relation expressions:

The Heating mode in winter days:

$$P = 0.0000597\, t_w^3 - 0.00613\, t_w^2 + 0.83\, t_w - 10.494 \quad (1)$$

The refrigerating mode in hot days:

$$P = 0.000145\, t_w^3 - 0.00379\, t_w^2 + 0.3167\, t_w - 5.509 \quad (2)$$

Where P = compressor power consumption (W)

t_w = outdoor temperature (℃)

According to formulas 1 and 2, it is possible to get the compressor power consumption at any temperature in the whole year, and then the operation costs could also be got.

3. Operating cost per unit area

Operating cost per unit area = annual operating costs / air conditioning area (3)

3.2.3 Economical comparison

With the following cases as the examples, this chapter compares the ground source heat pump system with other traditional air-conditioner on economy.

3.2.3.1 The residential building in Hefei

In this case, the building area is 3255 m^2. Different air-conditioning solutions were compared based on the initial investment and operation fees.

TABLE 4. Economical comparison (Li Tie, 2003, 24.)

No.	System mode	Initial investment (Thousand Euros)	Operating fees per 8 hours (Thousand Euros)
1	Ground source heat pump system	101.25	Heating: 4.84 Refrigeration: 4.22
2	Central heating	63.12	Heating: 6.32
3	Gas water heater	43.1	Heating: 9.45
4	Fuel heater	43.65	Heating: 9.96
5	Electrical heater	50.85	Heating: 10.95
6	Air cooling conditioner	36.77	Refrigeration: 5.49
7	Water chiller	58.81	Refrigeration: 4.41
8	Air source heat pump	75.05	Heating: 5.75 Refrigeration:4.61

FIGURE 8. Economical comparison (Li Tie, 2003, 25.)

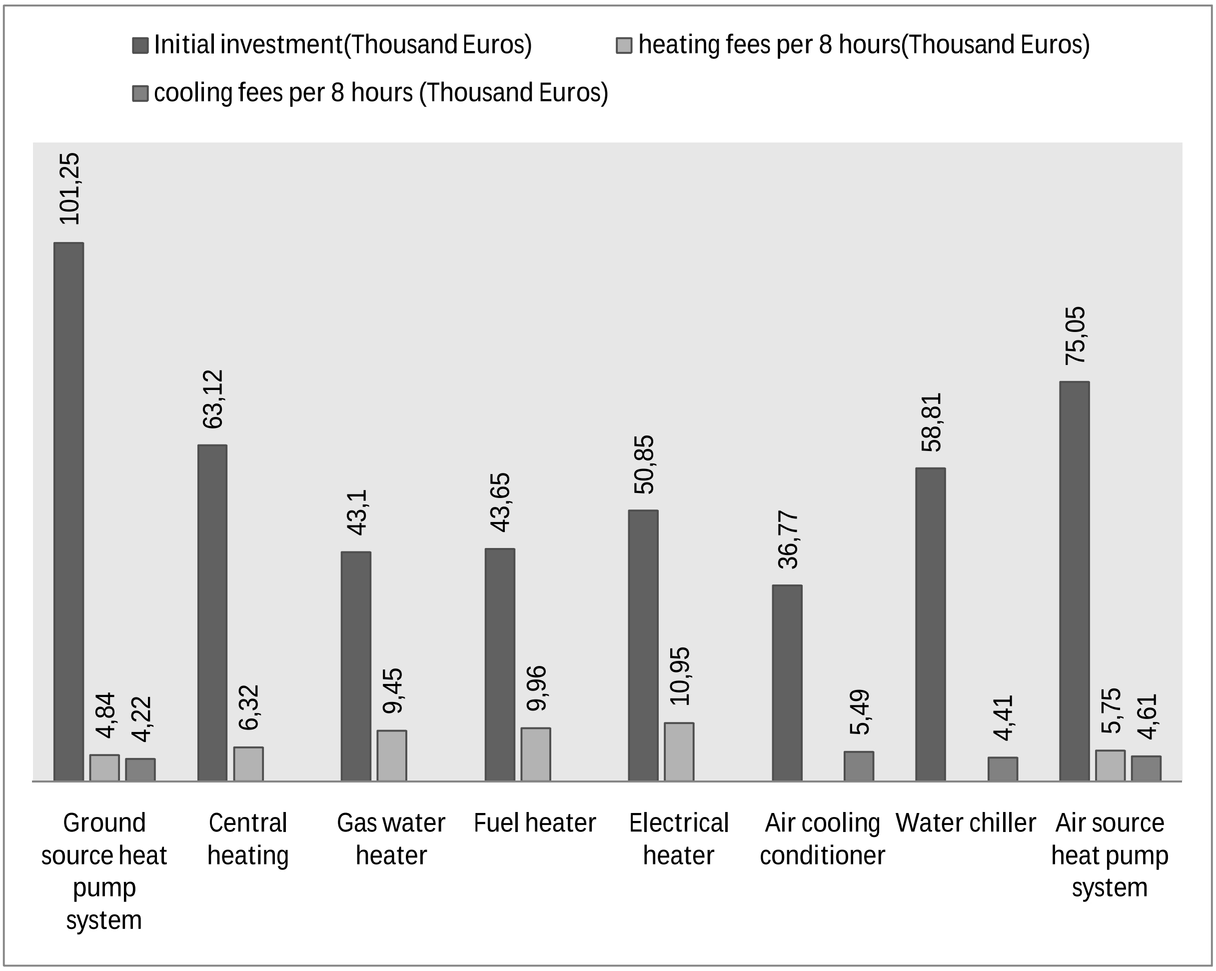


TABLE 4 and FIGURE 8 show the initial investment costs and the operation fees for different heating and refrigeration system. As we can see from the chart, the ground source heat pump system has the highest initial investment, but the operation costs are relatively cheap. It means that a ground source heat is the most economic way for long term using. Not only with the cheapest long-term operation costs, the ground source heat pump system is a dual-purpose machine, and it has a vast potential consumer market in warm summer and cold winter regions.

3.2.3.2 The Sino-U.S. renewable energy cooperative projects - Concordia Plaza in Beijing

The largest ground source heat pump system in the world is at the Galt House East Hotel in Louisville, Kentucky. The system heats and air-conditions 600 hotel rooms, 100 apartments, and 89,000 m^2 of office space. Energy savings, when compared to a similar traditionally designed building complex, are about 53 percent.

Concordia Plaza was the second largest building using the ground source heat pump system when completed. The total construction floorage is 88,000 m^2, and the heat pump system is the most advanced model with better technology than before.

TABLE 5. Condition of the Building (Jike Geothermal Heat Pump, 2005)

Building type	high-end apartment
Building area	14,175 square meters
Heating area	70,000 square meters
Heating exchange capability	4104.1 kW
Noise level:	Room noise ≤30dB
Refrigerator effects	temperature 38 ℃ in the sunshine, outdoor temperature 25 ℃
Heating effects	outdoor temperature -10℃, outdoor temperature 20 ℃
Operating effects	Wind supply evenly, the maximum temperature is 1 ℃, the gas velocity is less than 0.3 m per second. Air quality is much better than air blower plate tube system.

TABLE 6. Economic Contrast (Jike Geothermal Heat Pump, 2005)

<table>
<tr><td colspan="2">System</td><td colspan="2">Ground source heat pump</td><td colspan="2">Traditional central air conditioning + gas fired boiler</td></tr>
<tr><td colspan="2">Cost</td><td>Unit area price (Euros/m²)</td><td>Total price (thousand Euros)</td><td>Unit area price (Euros/m²)</td><td>Total price (thousand Euros)</td></tr>
<tr><td rowspan="2">Total invests</td><td>Equipment costs</td><td>212.8</td><td>1493.4</td><td>208.05</td><td>1457.20</td></tr>
<tr><td>Installation costs</td><td>129.2</td><td>904.4</td><td>139.65</td><td>977.55</td></tr>
<tr><td colspan="2">Total</td><td>342</td><td>2397.8</td><td>347.7</td><td>2424.76</td></tr>
<tr><td rowspan="2">Annual operation costs</td><td>Heating</td><td>12.26</td><td>142.6</td><td>24.91</td><td>252.89</td></tr>
<tr><td>Refrigeration</td><td>8.07</td><td></td><td>11.22</td><td></td></tr>
<tr><td colspan="2">Housing compensation</td><td>2375</td><td>35.6</td><td>2375</td><td>83.125</td></tr>
</table>

TABLE 5 is the condition of the building and the requirements for heating and refrigeration. TABLE 6 shows the costs of investments and operation for two kinds of air condition systems. As we can see from the table, compared to traditional central air conditioner, the ground heat pump has obvious advantages in many aspects. The total costs are reduced 1.5%, the annual operation costs are reduced 43.6%, and the housing compensation is reduced 57%. Because of so many advantages and the technology is relatively new, the equipment costs are a little bit more expensive, and that is the main reason for people not to choose them. However, thinking about the installation fees, operation costs and other costs, the ground source heating system is actually an economic and green choice.

3.2.4 Conclusion

Because a boiler just transfers 90% of electricity or 70%-90%of fuel internal energy into the heat for heating. Comparing to an electrical boiler heater, the ground source heat pump will save two thirds of energy. Comparing to a fuel boiler heater, the ground source heat pump could save half of energy.

The ground has a stable temperature about 10-25 ℃ all year round, and the ground source heat pump always has a relatively high efficiency for both heating and refrigeration processes. As a result, in recent decades, the ground source heat pump system has developed rapidly in North America, Central Europe and North Europe. In China, the market is also increasing year by year. It is expected that ground source heat pump technology will be the most effective heating and refrigeration air conditioning technology.

4 METHOD STATEMENT OF GROUND SOURCE HEAT PUMP

From what has been introduced and analyzed in previous chapters, such conclusion can be obtained that the ground source heat pump will instead of the traditional heating and refrigeration system. Comparing to traditional way, the ground source heat pump system has longer lifecycles, lower noise levels, higher energy efficiency ratio and less pollution emission. However, the high initial costs have severely limited the general use of the heat pump. In the initial investment of ground source heat pump system, the ground heat exchanger is the biggest factor. On the other hand, ground heat exchanger is an important part of the ground source heat pump system and it's also the main difference compared to other traditional air-conditioning systems. Whether the selection of the type is reasonable or whether the design is scientific have much to do with the performance and the economy of the ground source heat pump system.

4.1 The design of the ground heat exchanger

The design of the ground heat exchanger for the close loop ground source heat pump should include the following aspects.

4.1.1 Determine the heating and refrigeration load

Design load is the primary reason for selecting the air conditioning terminal devices, heat pump capacity and relevant auxiliary equipment. The calculation of the design load should be based on the local design standards and work condition. In order to determine the maximum load, the load of each room needs to be calculated hourly, and the largest one should be chosen. The calculation is necessary for further analysis of the energy consumption of the ground source heat pump system. Several commonly used energy consumption calculations are Degree-day procedure, Bin method and Hour-by-hour method.

1. Degree-day procedure, which is the simplest, however, gives the poorest results. When the efficiency of the operation depends on the outside air temperature, this method becomes not applicable.

2. Bin method, which is relatively simple and accounts for the changing outdoor temperature and partial load conditions. This method is often used on single family residential applications.

3. Hour-by-hour method is using one of the many software programs available for these calculations. This method is often used for large commercial and institutional systems where considerable amount of details is required to make a good analysis. (Geothermal Heat Pump System, 1995)

4.1.2 Determine the pipe pattern of the heat exchanger

Nowadays, there are two main types of pipe pattern of the heat exchanger. They are horizontal heat exchanger and vertical heat exchanger. The selection depends on the area of the ground, the local soil type and the mining costs.

If the ground is large enough without hard rock, the horizontal way is more economical. If not much place for the installation, the vertical pattern is always the only choice. The horizontal heat exchanger is shallow buried that hand digging could be possible and the installation investment is relatively low, but its heat transfer performance is much worse than the vertical heat exchanger's. In fact, the land area is always limited in China, so the vertical heat pump is the most widely adopted.

4.1.2.1 Horizontal heat exchanger

There are kinds of horizontal heat exchangers, such as, single trench single pipe, single trench two-pipe, single trench two-layer two-pipe, and single trench two-layer four-pipe. (See FIGURE 9) In multi-layer system, the pipes in lower layer are surrounded by a stable temperature. So, the heat exchange rate is better than single layer system. Furthermore, multi-layer heat exchanger covers less area than single layer system.

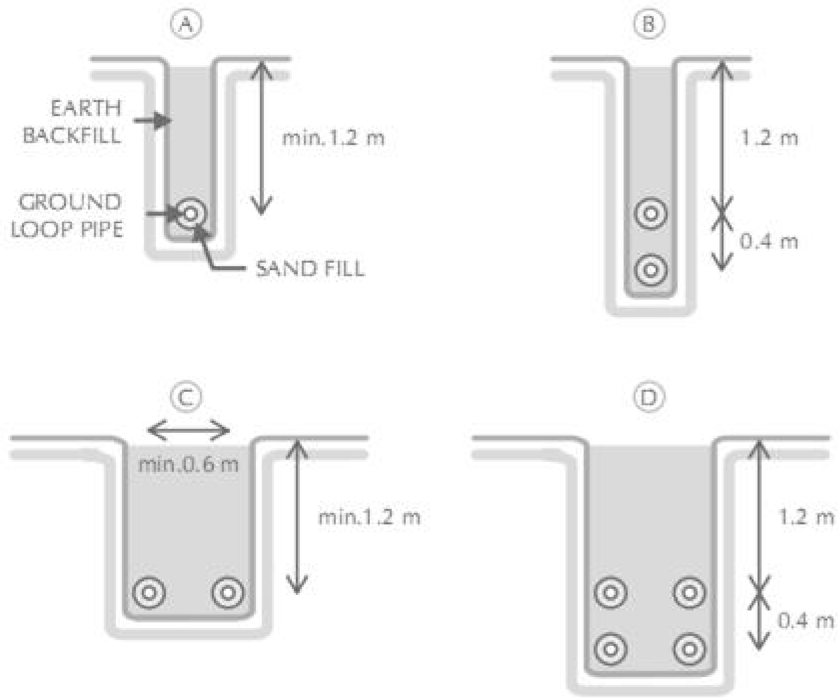
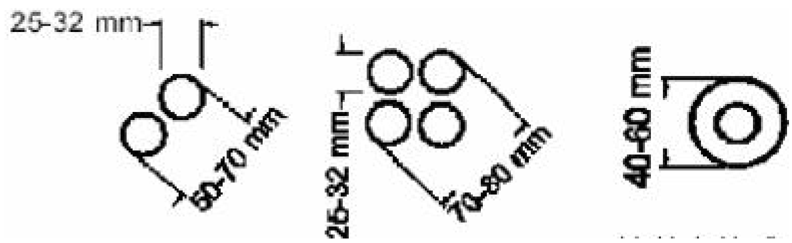


FIGURE 9. Pipes pattern of horizontal heat exchanger (Minister of Natural Resources Canada, 2001 – 2005, 15.)

As a rule of thumb, the best depth for single layer heat exchanger is 1.2–2.0 m, and 1.6–2.4 m for two-layer heat exchanger. Anyhow, the pipes should be buried under the freezing zone.

4.1.2.2 Vertical heat exchanger

Vertical ground source heat pump system is well suited to larger buildings where the damage to the ground needs to be limited or there is just not enough ground for fixing the heat exchanger.



Single-U-pipe Double-U-pipe Co-axial

FIGURE 10. The dimension of heat exchanger (Sanner, Burkhard, 2008, 10.)

FIGURE 10 shows three types of borehole heat exchanger which have been most commonly used; they are Single-U-pipe, Double-U-pipe, and Co-axial. The following paragraphs will describe them in detail:

1. U-pipe

U-pipe is composed of pipe and tie. The pipe is set into a tube well with a diameter of about 100-150 mm, the depth is 10-200 m, and the diameter of the pipe is less than 50 mm (the flow should be limited). Compared to any other vertical heat exchanger, U-pipe is more convenient for installing. It can support high pressure and has few tie and no leaking. Because of those benefits, U-pipe is most widely used nowadays.

FIGURE 11 shows a new applying technology of U-pipe. In some projects abroad, U-pipe is tie up on the steel truss of pile foundation and covered by concrete, it can take little space, and saves the land cost. It is called pile-foundation heat exchangers technology.

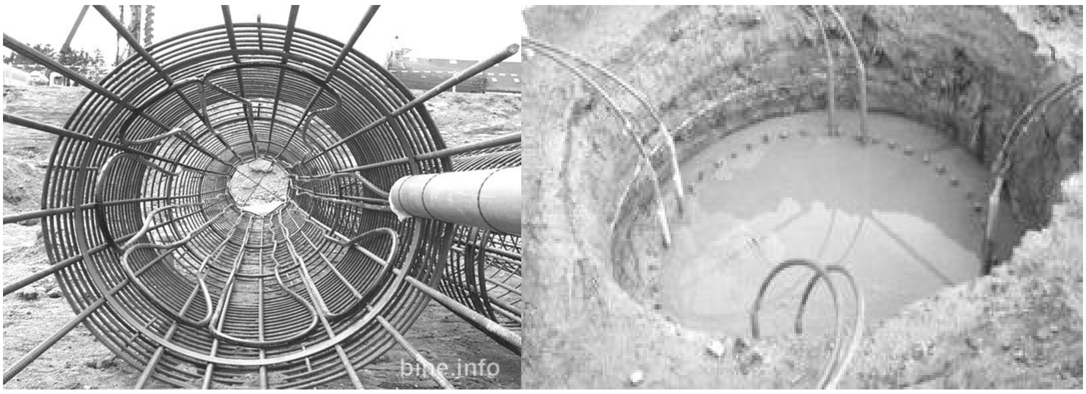


FIGURE 11. Pile-foundation heat exchanger (BINE informationsdienst, 2010)

2. Co-axial

Co-axial pipe i consists of two pipes with different diameter. The diameter of outer pipe is 100-200 mm, and the inner pipe is φ15- φ25 mm. Because the heat-exchange area between the outer pipe wall and solid is increased, the heat exchange efficiency of the co-axial is 16.7% higher than that of normal pipe heat exchanger. There are several disadvantages for the co-axial. One disadvantage is the big diameter of the outer pipe. It causes the difficulties in down pipe and high initial costs. Beyond that, the co-axial pipe has the risk of leaking in the complex joint.

4.1.3 The material-selection for the underground pipe

Generally speaking, once the ground source heat exchanger has been buried into the solid, it will be almost impossible to maintain and change it. So the material for the pipe should have good resistance to heat and chemical erosion. At present there are two common materials for the underground pipe: metal and plastic.

4.1.3.1 Metal pipe

Copper, aluminium alloy and stainless steel are three most common materials for underground pipe. The stainless steel is very expensive; it can just be used on the straight drinking water pipe for outdoor installation. Copper pipe also has a relatively high price, and when it is set into the ground, the specific plastic sheath is needed for preventing corrosion. Aluminium is a new type of pipe with cheap price and light weight; however, it can also corrode in alkaline environment. The FIGURE 12 shows the corrosion process of aluminium alloy.

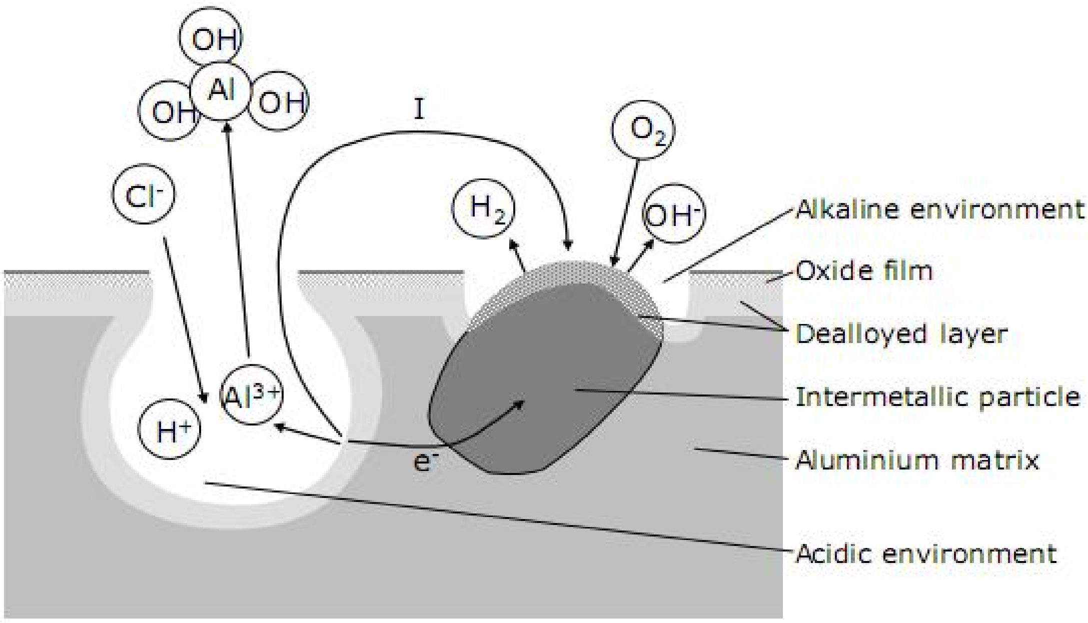


FIGURE 12. Corrosion of aluminium alloy (Davis, J.R. 1987, 104.)

In 1960s, heat exchanger pipes were usually metallic. Because of bad corrosion resistance, most of them got rotted in 10-20 years. It did not only reduced the service life, but also held back the development of the heat pump technology.

4.1.3.2 Plastic pipe

From 1970s, resin started to be used in the heat exchanger pipe. Plastic pipe is light weight, it is easier to install than metal pipe, faster to install as well as more cost effective than metal pipe. A well installed and well maintained plastic pipe heat exchanger system could have a life cycle of up to 50 years. Plastic pipe has brought a great promotion in ground source heat pump technology; for it has high cost performance and it overcomes the shortcomings of the metal pipe. Plastic pipe is diversified and varied greatly in characteristics. The most common plastic pressure pipe systems are manufactured of UPVC, CPVC, PE, d. PB, PP-R, PE-X, and ABS.

The molecular structure and the plastics additives determine the material property. The service life of the plastic pipe depends on the four factors:

1) Ambient temperature and medium temperature

2) Pipe working pressure

3) Properties of the fluid media

4) Outer diameter and the thickness of the pipe

TABLE 7. Comparison of physical properties (Songjian, 2001, 77.)

Serial number	Material characteristics	Coefficient of linear expansion K^{-1}	Modulus of elasticity MPa	Coefficient of heat conductivity W/M*K	Expansibility N
1	PB	0.13	350	0.22	480
2	PE-X	0.20	600	0.41	2530
3	HDPE	0.20	800	0.43	2700
4	CPVC	0.08	3500	0.14	3100
5	PP-R	0.18	800	0.24	1780

TABLE 8. Comparison of fluid features (Songjian, 2001, 78.)

Material characteristics	External diameter *Wall thickness mm*mm	Inner diameter mm	Flow velocity m/s	Pressure loss Mpa/m
PB	40*3.7	32.6	2.4	1.84
PE-X	40*5.5	29.0	3.0	3.25
CPVC	40*4.5	31.0	2.7	2.36
PP-R	40*8.0	24.0	4.4	8.13

TABLE 7 lists physical properties of five pipes with same nominal diameter of 32 mm, same length of 10 m and the same temperature difference of 50 K, but different material characteristics. In order to get more information, TABLE 8 lists the fluid features about those pipes in the same outer diameter of 40 mm, the same fluid rate of 2 L/s and the same working environment of 70 ℃ and 1 Mpa.

Based on the comparison of TABLE 7 and TABLE 8, it is easy to find that the PB pipe is the thinnest and with the lowest expansibility. It has best fluid features and physical property. However, the price of PB pipe is very expensive in China; it’s two times the price of copper pipe. Close to PB, PE-X is also a pipe material with good performance. Almost all PE-X is made from high density polyethylene (HDPE). PE-X contains cross-linked bonds in the polymer structure, changing the thermoplastic to a thermoset. PE-X pipe has high elasticity and ductility, so it can effectively avoid the damage caused by stratigraphic changes. Compared with all above, the combination property of CPVC and PP-R pipe is not good, and the price of the PP-R is relatively high in China.

4.1.4 The choosing of antifreeze agent

In the heating process, if the temperature at the exit of the evaporator is under 2 ℃, antifreeze agent should be used as the heat-transfer medium. Based on this standard, in China, excluding some southernmost areas, antifreeze is used in heat exchanger to protect from freezing.

A good antifreeze agent should meet the following requirements: safe, innocuity, noncorrosive, good properties of heat transfer, low costs and long service life. There are three common types of antifreeze agent:

1) Salt solution ($CaCl_2$ or NaCl)

Generally speaking, salt solution is safe, cheap and innocuity. it also has good heat transfer property and long service life. However, it has corrosive action on metals in the air. Only when the air is totally pumped out from the system, salt solution will be the optimal choice for antifreeze. Practice shows that the $CaCl_2$ solution can work well under the temperature of -4 ℃ in northern China.

2) Glycol (vinyl glycol or allyl glycol)

Glycol is also safe, noncorrosive, and it has a good heat transfer property and reasonable price. However, it is poisonous, expensive and has short service life. The stickiness of the glycol increases when the temperature drops down. That will consume lots of power of circulation pump. Glycol can work well in south part of China, where the operation temperature of the heat exchanger loop is above 2 ℃.

3) Ethyl alcohol (methyl alcohol or ethanol)

Explosion may happen when the ethyl alcohol is mixed with air, so ethyl alcohol is not safe when it fails to be managed. Additionally, methyl alcohol is poisonous. But methyl alcohol is noncorrosive, reasonable priced and it has long service life. The ethyl alcohol needs to be diluted by same volume of water. It is widely used because of its non-corrosiveness.

In order to decrease the corrosion rate of metal or alloy, a chemical compound is always added into the antifreeze agent. It is called corrosion inhibitor. Nevertheless, most of the corrosion inhibitors are poisonous.

4.1.5 Determine the length of underground pipe

1) Horizontal ground-coupled heat pump

The length of underground pipe can be calculated by using heat transfer capability. Heat transfer capability is heat exchange per unit pipe. The heat transfer capability of a horizontal ground-coupled heat pump is about 20-40 W/m. We can use the lower limit for length design.

The calculation formula of one trench single pipe is:

$$L = 2 * Q_1 * 1000 / 20 \quad (5)$$

Where L = total length of coil (m)

Q = the capability of heat absorbing from the ground in winter (kW)

20 = the heat transfer capability per meter (W/m)

2) Vertical borehole ground-coupled heat pump

The heat transfer capability of vertical single-U-pipe is about 60-80 W/m. The heat transfer capability of vertical double-U-pipe is about 80-100 W/m we can also use the lower limit for length design:

The calculation formula of one trench single pipe is:

$$L = 4 * Q_2 * 1000 / 80 \quad (6)$$

Where L = total length of coil (m)

Q_2 = the capability of heat absorbing from the ground in winter (kW)

80 = the heat transfer capability per meter (W/m)

Compared to a horizontal ground-coupled heat pump, the vertical borehole ground-coupled heat pump will save half of pipe to get the same amount of heat from solid. The calculation for the length of heat pump exchanger is especially for the ground source heat pump, but it is not needed for traditional air-conditioning. Nowadays, there are many calculation ways to get the length of the heat exchanger pipe. However, up to now there are no unified standard in the world.

4.1.6 The calculation of pressure loss of the pipe

The total pressure loss in the system results in the combined losses due to elevation changes and friction. In a heat exchanger system, water pressure is created by the circulation pump. Calculating pressure losses is necessary for determining the appropriate size for the pump. The selection of the circulation pump depends on the cycling water amount and the type of antifreeze agent.

4.2 The analysis of heat transfer performance analysis

The design for the air conditioning system is varied. Whether using traditional air conditioning or ground source heat pump will have no big difference in indoor part designing. The ground source heat exchanger is the essential difference between them. The key point of spreading the ground source heat pump technology is analyzing the heat transfer performance and offering some proposals for the heat exchanger designing.

4.2.1 The particularity of the underground heat exchanger

Different from the common heat exchanger, the underground heat exchanger does use the heat transfer between liquid and liquid, but the heat transfer between the liquid and solid. This is a totally special exchange procession which is complex and non-stable. There are no existing experiences to be followed in exchanger design. So, the thorough research needs to be done to the exchanger in order to carry out adaption and promotion.

4.2.2 Heat transfer model

In order to analysis the performances of heat transfer, a theoretical model of heat transfer need to be explained. The purpose for heat transfer modelling is to build up the distribution of ground thermal field in working condition of heat exchanger. One-dimensional unsteady heat conduction which was developed by Ingersoll and Plass in 1948 is the most common theoretical foundations for most heat transfer modelling.

4.2.3 Heat transfer analysis

The calculation of heat exchanger is based on the heat transfer analysis for single borehole. The situation of multiple boreholes is just the extension of the single borehole.

In refrigeration working condition, the fluid transfers the heat to the ground. In heating working condition, the fluid absorbs the heat from the ground. They are using the same heat transfer model, although the direction is different. Heat flow needs to overcome the thermal resistance when it transfers from the pipe fluid to the thermostatic ground. The thermal resistance consists of four parts:

1) Convective thermal resistance: the resistance existing in convection heat transfer process between fluid and the inner surface of the pipe.

2) Pipe thermal resistance

3) Borehole thermal resistance: the resistance between outer surface of the pipe and the borehole surface. Because air is a natural insulator, grouting is the most common material for backfill. Standard grout actually has a high thermal resistance, so the borehole diameter should be minimized to limit the grout's affect.

4) Ground thermal resistance: the resistance from borehole surface to thermostatic ground.

4.3 Project case of heat exchanger design

In order to get a better knowledge and deeper understanding, a case of heat exchanger design for Auditorium of Anhui Architecture & Engineering institute will be studied and analyzed. (GSHP department of Anhui Architecture & Engineering institute, 2003)

4.3.1 General situation of the project

The two stories building in FIGURE 13 is the Auditorium of Anhui Architecture & Engineering institute. The first floor is the place for study lounge; the top floor is the place of academic hall.

The area of each floor is 500 m^2. There are 480 seats in the academic hall, there the refrigeration load is about 110 kW, and the heating load is 80 kW.

FIGURE 13. Auditorium of Anhui Architecture & Engineering institute

The project selected the vertical borehole ground-coupled heat pump system as the air-conditioning. The heat exchanger was laid down under the lawns in front of the building. It covered 250 m^2. The burial depth of horizontal part was 2 m; the tube well was 62 m deep, and 25 wells had been drilled. The total length of the heat exchanger was 3000 m. The titular refrigerating capacity of the heat pump units is 130 kW, and the titular refrigeration heating capacity is 100 kW. The academic hall used centralized air conditioning system as terminal devices. The air output is 20000 m^3/h.

4.3.2 The design of the heat exchanger

The following aspects were considered when designing the heat exchanger for ground-coupled heat pump system.

a) Choosing the heat pump unit

In accordance with the building area and the type of air-conditioning terminal system, the water-water heat pump units are the best choice. Because the refrigeration and heating efficiency of ground-coupled heat pump system (close loop) is not as high as groundwater heat pump system (open loop), the titular refrigeration and heating capacity is more than real capacity.

b) Choosing suitable pipe pattern of the heat exchanger

Considering the practical situation, the design used a vertical borehole ground-coupled heat exchanger. Grout was used for backfill material between the pipe and the tube well, so that the heat resistance could be reduced and the ground sewage could also be kept out of the well.

In general principle, the depth of the tube well is about 45-150 m; here the 62 m is reasonable depth. Comprehensively considered in area and heat exchange performance, the distance between each well was finally set to 4 m.

c) Selecting the heat exchanger pipe

At present the HDPE (high-density polyethylene) pipe was widely applied in China. Too fast velocity of the fluid could wastes the power of the circulating pump. On the other hand, too small velocity will limit the performance of heat transfer. In this project, the HDPE SDR11 was used with the outer diameter of 32 mm and inner diameter of 26 mm, and the velocity in pipe is 0.6 m/s.

d) Selecting the antifreeze agent

For the fluid temperature at the exit of the evaporator is less than 2 ℃ in the working condition. $CaCl_2$ was used as the antifreeze agent in the heat exchanger

e) Calculating the pipe length according to the pipe type and pattern

This is a particular aspect that needn't to be considered in traditional air-conditioning system. In this project the total drilling distance is 1550 m and the length of the pipe is 3000 m.

f) Choosing the right circulation pump to compensate the pressure loss

Compared with the metal pipe, the plastic pipe has much less frictional resistance. The distance between the heat exchanger and the heat pump unit is not big, that made little pressure loss during the fluid cycling. However, to prevent clogging of the U-pipe by impurities, a dirt separator was installed in the entrance of the feed pipe.

4.3.3 Operating efficiency

After testing, the heat exchanger can fit the system quite well, and is certified to be competent.

1) Noise level: <= 40 dB

2) Refrigeration effect: The indoor temperature can be less than 25 ℃, when the outdoor temperature is 37 ℃.

3) Heating effect: The indoor temperature can be over 20 ℃, while the outdoor temperature is -9 ℃.

4) Running effect: homogeneous air supply can be realized. The air speed is less than 0.33 m/s, the maximum temperature difference is in a range of 2-3 ℃.

5 Results

After studying and analyzing the ground source heat pump with air conditioning system from both technical and economical aspects, it could be conclude that as a new heating and refrigeration technology, the ground source heat pump system has good operation performance and economy.

Comparing to traditional heating and refrigeration systems, the ground source heat pump with air conditioning system has following advantages.

1. Multifunction of one machine

   Because it is not subject to the impact of changes in ambient temperature, the ground source heat pump with air conditioning system can efficiently work in various kinds of geographical and climatic environment. It can heat in winter, refrigerate in summer, and it can even supply with domestic hot water the whole year.

2. Green and energy-saving

   By using the renewable energy from the ground, the ground source heat pump system will save the electricity and reduce the dependency on boiler; it will greatly decrease the emission of green house gases.

3. High energy efficiency and low operation costs

   Compared to 175-250% for air source heat pumps, the ground source heat pump systems reach fairly high efficiencies (300-600%) on cold days. Even though the installation price of a ground source heat pump system can be several times that of an air source system of the same heating and cooling capacity, the additional costs are returned in energy savings in 5–10 years. (Energysavers, 2011)

4. Long life and low maintenance

   The ground source heat pump is reliable. That is because most of the operation parts are buried under ground or installed in the building. Nowadays, the lifetime of the underground heat exchanger is up to 50 years. The heat pump unit has over 15 years service life as well. Without the annual cleaning for the cooling tower and the scale removing for boiler, ground source heat pump almost need fewer maintenance.

Nevertheless, like almost anything else, the ground source with air conditioning system is not perfect. From the study, it can be found that there are two reasons that diminish the application of ground source heat pump.

1. Venue constraint

The heat transfer happens underground, so a deep borehole or a long trench needs to be dig. In China, it always only is applied in large-scale communities and villas.

2. High initial investment costs

Although the operation fee and maintenance costs of the ground source heat pump with air conditioning system is relatively cheap, the initial investment is much higher.

By and large, the ground source heat pump with air conditioning system has more advantages than disadvantages. With the increasing of the income, the development of the ground source heat pump technology and the encouraging national policy. the disadvantages will be offset one by one.

6 Conclusion

As a proven technique, ground source heat pump technology has been widely used in European and American countries. However, in China, the technology is fairly new and the application of the ground source heat pump system is still in its infancy now. Although the government is strengthening the policy guidance for ground source heat pump, people has little knowledge about this new technology. The high initial investments costs always make no one even want to know about it.

For this reason, the thesis compared the ground source heat pump with air conditioning system to any other traditional air conditioning system in terms of technology and economy. Data and figures are used to show everyone the advantages of a ground source heat pump system. Several project cases are also here to prove that the ground source heat pump air condition system is economically feasible to be chosen and applied.

The heat exchanger is an essential part of the ground source heat pump system and sets it apart from its competitors. In the last part of the thesis, practical instances were added to explain the designing procedure and method for heat exchanger.

The ground source heat pump is an advanced but complex system. In order to simulate the industrialization of the heat pump system and generalize it, the following measures need to be taken.

1. Establish and improve the laws and standards for heat pump systems.
2. Optimize the design and calculation can be consulted for engineering.
3. Develop new type of pipe and other related products.
4. Enhance the training for heat pump designers and builders.
5. Co-operate with international research and development institutes and manufacturers

The belief is that, the ground source heat pump with air conditioning system has great values in practical application and bright prospect in marketing. Based on the foreign development experience, with the support of the government and the hard work of technicians, this technology will be greatly improved in China and extend to the whole society.

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